Application of digital image correlation to size effect tests of concrete

Syed Yasir Alam, Ahmed Loukili

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Application of digital image correlation to size effect tests of concrete

S. Yasir Alam & A. Loukili
Research Institute of Civil Engng. And Mechanics (GeM) Ecole Centrale de Nantes, France.

ABSTRACT: The structural size effect on mechanical response of quasi-brittle materials is generally attributed to the stable growth of fracture process zone or microcracking ahead of the propagating crack before maximum load is reached. The process of microcracking essentially depends on the heterogeneity of material microstructure and its presence reduces the speed of the propagating crack. The purpose of this study is to identify the cracking phenomenon and the process of crack propagation in geometrically similar concrete beams. Three point bending tests are performed on scaled concrete beams in accordance with RILEM recommendation of size effect test. A non contact method using Digital Image Correlation technique is applied on the surface of concrete beam to capture crack propagation in two dimensions. The technique is found very effective to measure the crack growth in concrete.

1 INTRODUCTION

Structural size effect is a central problem in the modeling of fracture. Fracture tests are normally conducted on relatively small specimens and then this information is extrapolated to large structures. Size effect has become a crucial consideration in the efforts to design concrete structures, for which there is a large gap between the scales of large structures (dams, reactor containments, bridges) and of laboratory tests.

In concrete structures, fracture is generally preceded by a gradual dispersed microcracking that occurs within a relatively large fracture process zone ahead of the crack tip of a continuous crack. Bazant (1984) demonstrated that fracture of this type may be modelled as the propagation of a band of uniformly and continuously distributed cracks with a fixed width w_c at the crack front. However, at a certain distance behind the crack band front, the distributed cracks coalesce into one major crack. He suggested that the width of w_c of the crack band must be treated as a material property, or else consistent numerical results independent of the method of the analysis could not be obtained. He made a hypothesis that the total potential energy release W caused by fracture is a function of both

1. The length a, of the fracture (crack band).
2. The area of the cracked zone $nd_a a$ or yielding zone in elasto-plastic crack.

where, nd_a is a material parameter and a is the length of the crack at the maximum load. Thus, the problem of size effect was treated with the following three assumptions, (Bazant 1984, 2002):

1. The length a, of the crack at maximum load is approximately proportional to the structure size D.
2. The slope of the effective boundary of the stress relief zone, k, is a constant when size is varied.
3. The size $w_c = nd_a$ of the fracture process zone is essentially a constant, related to inhomogeneity size of the material.

Since, the fracture mechanism in concrete is very complex and due to the limitations of the experimental techniques, the experimental verification of the above assumptions is still ambiguous.

Numerous experimental results have shown that for concrete specimens with geometrically similar dimensions the fracture energy increases and strength decreases with the increase in size of the specimen (Duan et al. 2002, Wittmann et al. 1996). Griffith (1920) presented a crack theory based on which, the crack would extend rapidly and specimen would rupture when the rate of release of strain energy attains a critical value. Kaplan (1961) studied the crack propagation in concrete. He calculated the critical strain energy release rate based on Griffith crack theory. He found that the smaller beam show lower critical strain energy rate than the larger beam. Crack extension was observed with the help of a staining technique. Slow crack extension is noted prior to instability or fracture. It was suggested that the rate of crack growth may be affected by the rate of loading and the size of the specimen.

The present paper is aimed to identify the cracking phenomenon and study the crack propagation in geometrically similar concrete structures. Three point bending tests are performed on scaled concrete beams following the RILEM 1990 recommendations for size effect. A non contact method using Digital Image Correlation (DIC) technique is applied on the surface of concrete beam to capture two dimensional crack propagation.

2 FRACTURE AND DAMAGE MEASUREMENT

For fracture or damage analysis and appropriate constitutive model establishment of the cement based composites, experimental examinations have shown importance to evaluate the cracking and damage behaviour with the development of micro-cracks ahead of the propagating crack tip; and energy dissipation resulted during the evolution of damage in the structure. The techniques usually used in such experiments may be the holographic interferometry (Mobasher, Shah et al. 1990), the dye penetration (Swartz & Go 1984, Swartz & Refai 1989), the scanning electron microscopy, the acoustic emission (Shah 1995), etc. These methods offer either the images of the material surface to observe micro-features of the concrete with qualitative analysis, or the black-white fringe patterns of the deformation on the specimen surface, from which it is difficult to observe profiles of the damaged materials.

2.1 *Digital Image Correlation*

Recently digital image correlation (DIC) has developed into a stable and reliable tool for fracture/damage measurement (Shah 1995, Sutton et al. 1985). In contrast to the more traditional methods it is a robust technique, with high degree of measurement accuracy and much easier to apply experimentally. The DIC technique requires minimal or no surface preparation and provides surface displacement data as the primary output. It is demonstrated that digital images of deformed objects could be analyzed to estimate the in-plane displacements of various points on the surface. The analysis methodology employed the basic continuum mechanics theory of deformation to develop and implement a procedure for estimating surface displacements.

The experimental procedure starts by creating a random black-and-white dot pattern on the specimen surface. These patterns, one before and one after the load application are then imaged by a digital camera and stored in a computer in a digital format. In the current work, the random pattern is painted on the specimen surface and captured using a digital camera while the crack was propagating. During the imaging process, the intensity of the random pattern is transformed into a finite number of samples on a rectangular grid. Each sensor, or pixel, in a typical digital camera averages the incident grey intensity to obtain a value, which is in the range of 0 to 256 for the intensity. To increase the accuracy of the correlation method, an interpolation scheme can be used to reconstruct a continuous intensity surface instead of a discrete intensity pattern. An optimized 4 tap spline interpolation scheme is used in our current study. Thus the use of higher interpolation function eliminates the errors like lens distortions, vibrations, periodic bias (Sutton et al. 1988, Choi and Shah 1997) and improves the accuracy of the object deformation obtained by subset based DIC (Cheng, Sutton et al. 2002). The displacement field is then determined through the movement of the sample (or subimage) in an area defined as the correlation zone. The correlation consists of considering a subimage in the reference image and locating that subimage in the deformed image, where the maximum likelihood is achieved. In this study, a commercial software Vic2D is used to perform the image correlation. The size of subimage is taken as 21x21 pixels which is regularly spaced in the reference image (of size 1392x1040 pixels) in the form of a grid. The resolution of the system depends directly on the distribution of gray levels which depends on the texture of the material. To obtain a random pattern, a speckle pattern of black and white paint is sprayed onto the surface of the specimen. The images on the two faces of the specimen are captured using two digital cameras, which are placed in such a way to film central part of the beam, above the notch where the crack is expected to grow.

3 TEST PROCEDURE

The objective of this experimental program is to demonstrate experimentally the effect of size on the cracking mechanism in concrete. The experimental program consists of three point bending tests according to the recommendations of RILEM (RILEM 1990) to take account of size effect. This method allows to identify the fracture parameters (fracture energy G_f and the effective length c_f of the fracture process zone) in Mode I fracture. The tests are performed on three sizes of specimens, which are geometrically similar in two dimensions (i.e. height d and length $l=3d$), while the third dimension (thickness b) of the beam remains constant equals to 100mm for all three sizes of beams. The dimensions of the beams are selected with respect to the maximum size of aggregate used (d_a = 20 mm) in the fabrication of concrete (Fig. 1).

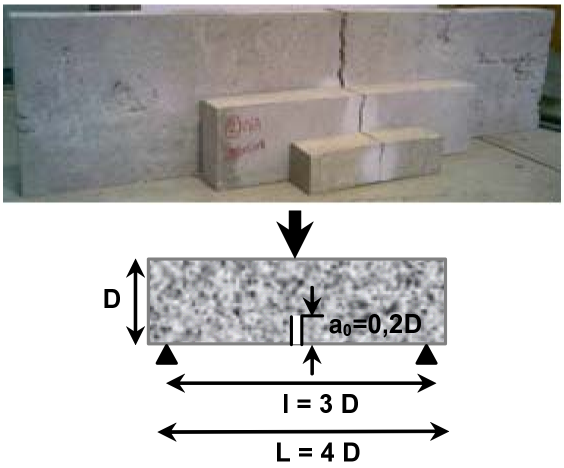


Figure 1. Geometry of the specimens.

The ratio d/d_a is 5, 10 and 20 and the ratio b/d is 1, 2 and 4 respectively for three sizes of beams. The beams are notched at midspan with a notch length *a*. The notch length *a* varies as the size of the beam varies with a constant *a/d* ratio of 1/5 for all the beams. The notch is created using a teflon plate of 3mm thickness placed in the mould before pouring the concrete. The plate is then removed after 24 hours.

Table 1. Concrete mix design details.

Cement (Portland 52.5)	312	kg/m^3
Sand	820	kg/m^3
Coarse aggregate (12 - 20 mm)	784	kg/m^3
Coarse aggregate (5 - 12.5 mm)	316	kg/m^3
Water	219	kg/m^3

The concrete used to prepare the beams is made from Portland cement type 52.5, sand, aggregate & water using the mix proportions as shown in table 1. A small quantity of superplasticizer is used in the concrete mix to increase the workability of the fresh concrete. The average compressive and tensile strength of cylindrical concrete specimens (Φ 10cm, h 20cm) is summarized in table 2. The dynamic modulus of concrete is determined using grindosonic apparatus.

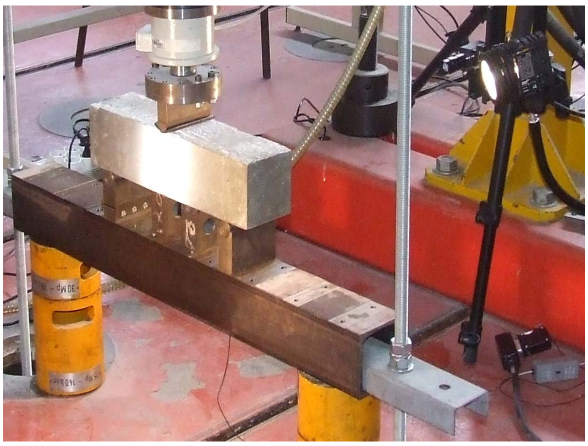


Figure 2. Test setup.

Table 2. Mechanical properties of concrete at 28 days.

Compressive strength, f_c'	45	MPa
Split cylinder strength, f_t	3.4	MPa
Dynamic Modulus, E_{dyn}	38	GPa

Three point bending tests are performed with a press of capacity 160 kN. The test setup is shown in Figure 2. A crack mouth opening displacement (CMOD) gauge (of gauge length ± 4mm) is used to measure the opening of notch. It consists of two blades each 10 mm in length attached to two metallic plates, one on either side of the notch at the bottom face of the beam. The metal plates are firmly attached to the specimen, which guarantee the perfect stability of plates and consequently the CMOD gauge. All three point bending tests are controlled with a constant rate of increment of CMOD equal of 0.05µm/sec as a feed back signal. This loading rate is used to achieve the peak load state in about 5 minutes.

4 RESULTS AND DISCUSSIONS

Three samples of each size of beam were tested. The test data obtained is the applied force and the notch opening displacement. The data is presented in Figure 3. It can be seen that the initial slope of the curve Force ~ notch opening is linear and is same for all the three sizes of the specimen. This can be true unless there is no localization of strain or damage. It can also be observed that the D1 and D2 beams show more nonlinear response as compared to the large beam D3, which means relatively high strain localization or damage accumulation. The post peak response also shows a size effect. For D3 the post peak response is more brittle which means the crack opening is relatively more unstable as compared to D2 and D1. The size effect on post peak response is usually described by relative stress versus relative structure deflection (Bazant 2004).

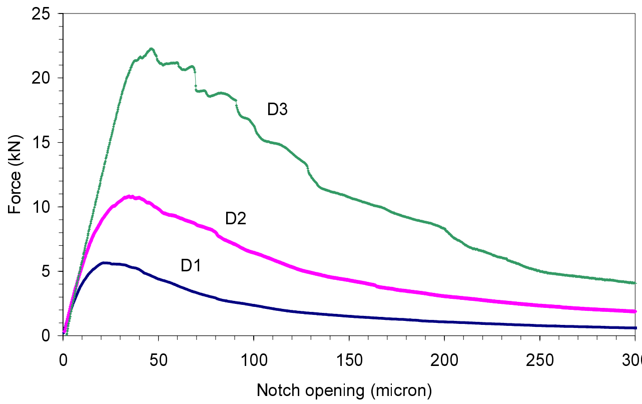


Figure 3. Load~notch opening response of geometrically similar beams.

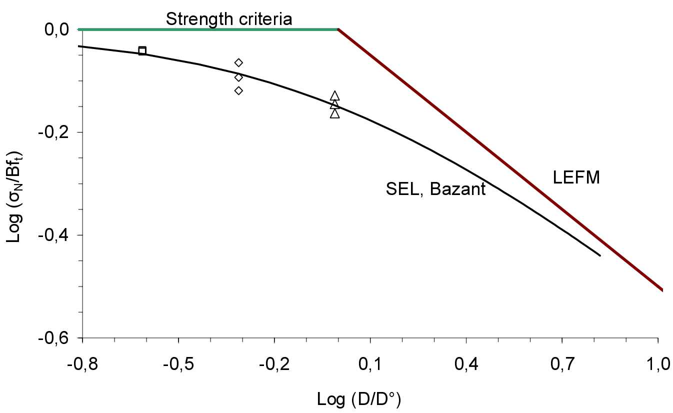


Figure 4. Size effect plot between nominal stress and size of the beams.

The size effect plot between the nominal stress and the size (depth) of beam is presented in Figure 4. The size effect law SEL (Bazant 1984) is also plotted and it predicts well the nominal stress for geometrically similar beams. The fracture parameters obtained from the test method are summarized in the table 3. The characteristic length of the material is calculated from equation 1 (Irwin 1958). The transitional size of the specimen D° is found to be larger than all the three sizes of the beams tested, which may be the use of large size aggregates in the fabrication of concrete.

$$l_{ch} = \frac{EG_F}{f_t^2} \quad (1)$$

Table 3. Concrete fracture parameters from size effect method.

Fracture Energy, G_f	234	N/m
Transitional size, $D°$	417	mm
Process zone size, c_f	9	mm
Bf_t	4.6	MPa
Characteristic length, l_{ch}	454	mm

4.1 *Digital Image Correlation*

The main aim of this experimental study is to apply digital image correlation to measure cracking is concrete. Notch opening displacement is measured using DIC during the experiment for all the beams. The result for a D2 beam is plotted against the load applied and is compared with the CMOD gauge measurement in Figure 5. The two measurements have shown a good agreement. The maximum difference obtained between the two measurements is about ± 5 microns which cannot be considered as an error since notch opening is calculated on a single surface.

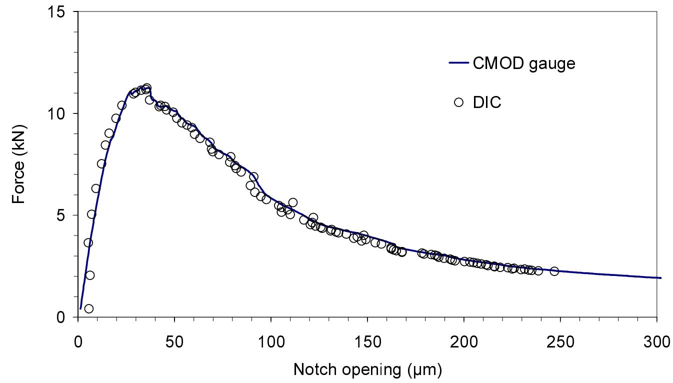
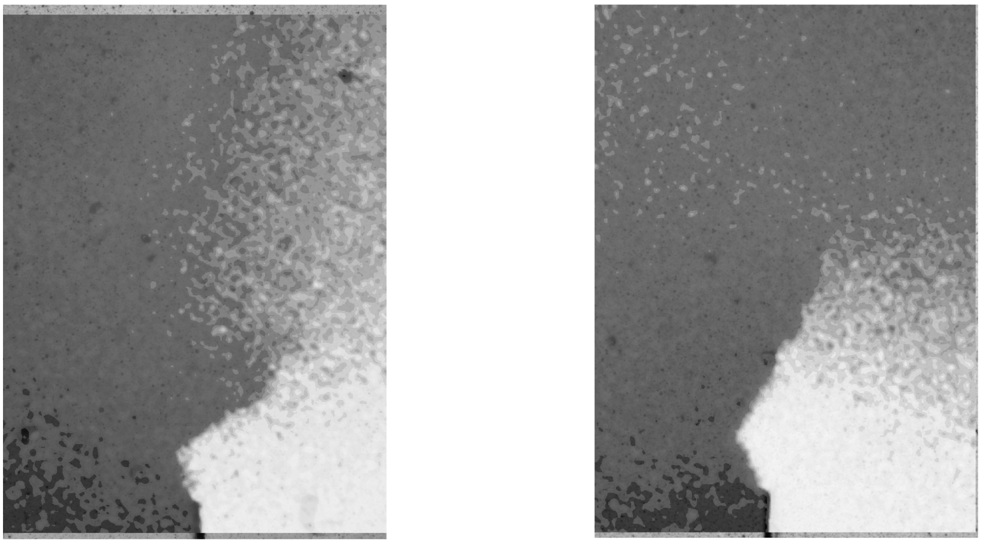


Figure 5. Measurement of notch opening displacement using CMOD capter and Digital image correlation technique.

The procedure used for measuring crack opening on the surface of the beam is presented in Figure 8. The displacement in X direction is plotted against position in X direction across the crack. A displacement jump can be noted at the crack line. This displacement jump occurs very sharply and increases as the load increases. Now, the crack opening displacement in X direction is measured as the displacement jump, which can be calculated by measuring difference between the two displacement levels. The notch opening presented in Figure 5 is measured in the manner.

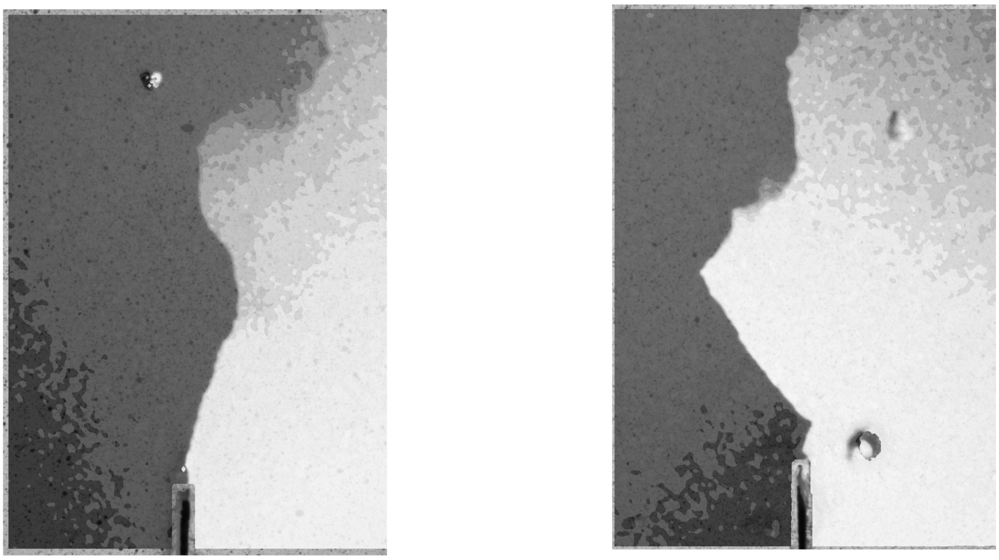
4.2 *Size Effect on Crack Propagation*

Tests are conducted on three sizes of specimen. DIC is applied on the two faces to observe the crack propagation on both faces. Correlated images of axial displacement at peak load are displayed in Figure 9. It can be seen that in D1 specimen, the crack size is relatively small and there is a zone ahead of the crack where the displacement jump occurs over a certain length. This can be considered as the zone of microcracking, where the macrocrack has not yet been created. This zone of diffused microcracking is a property of the quasi-brittle materials due to heterogeneity of the material. If the size of the heterogeneity is large, the size of the zone of diffused microcracking should be large. It can also be noted that both the faces of the specimen show a similar behaviour, which is important to predict the correct phenomenon of microcacking. Sometimes, due to eccentricity of the load or dissymmetry in the specimen geometry, the crack propagation on the both faces could be different.



Side A Side B

a) Small beam (D1)



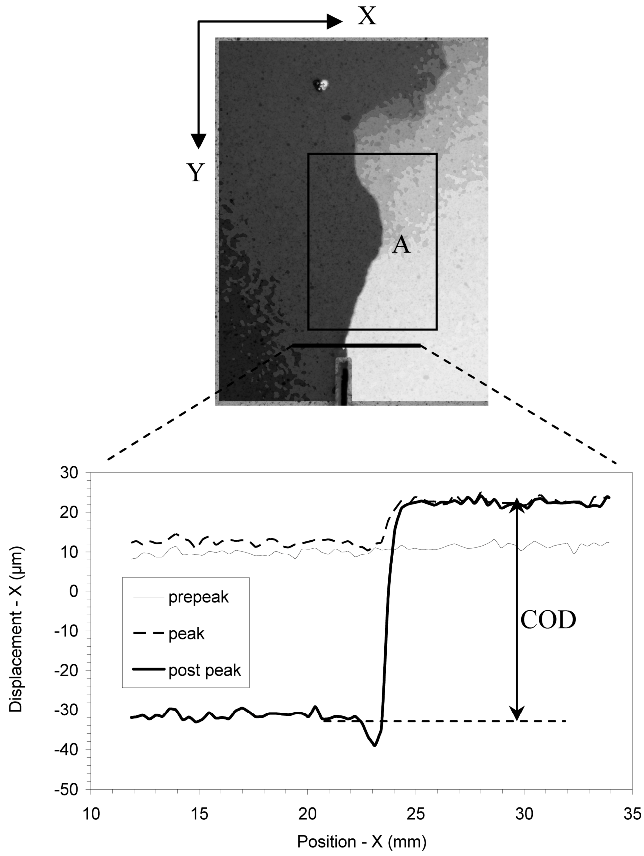
Side A Side B

b) Medium beam (D2)

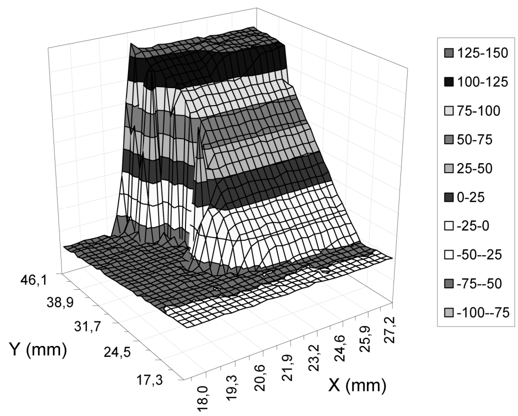
Side A

c) Large beam (D3)

Figure 6. Displacement field at peak load on three geometrically sized specimens.



(a)



(b)

Figure 7. (a) Measurement of crack opening displacement from DIC. (b) Displacement variation in area A.

4.3 *Size Effect on Crack Opening*

It is a general understanding that in a CMOD controlled test, when load~CMOD relationship is linear, crack does not grow from the notch (Shah 1995) i.e. the crack opening displacement at the tip of notch (CTOD) is almost zero. In our experiments the load~CMOD relationship is found linear in the pre peak region until about 60% of maximum force. Figure 9 presents the crack opening displacement for medium size beam (D2) at different stages of the test. A small crack opening in the range of 0.1-5 µm is measured ahead of the notch before 60% of the maximum load is achieved. After this stage, generally the structural response becomes nonlinear. The strains start to localize and the material develops a fracture process zone ahead of the crack. Following this the peak load is reached. At this stage the crack attains a certain critical opening and critical length, after which the crack becomes unstable i.e. the value of load starts to decrease with the corresponding increase in the crack opening and crack length. At this critical stage the opening of the notch is plotted against the size of the specimen in Figure 8. It is found that the notch opening is not proportional to the size of the beam.

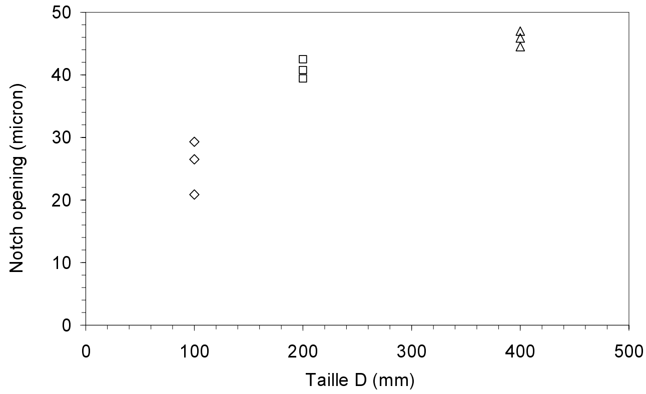


Figure 8. Notch opening corresponding to maximum load attained versus size (depth) of the beam.

Crack length can also be estimated based on the data of the crack opening displacement as shown in Figure 9. However, the technique is found inefficient to capture the exact size of the fracture process zone ahead of the crack.

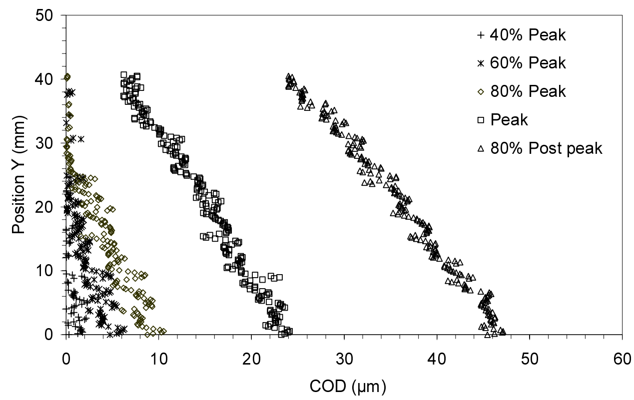


Figure 9. Evolution of crack opening displacement in D2 beam during the experiment.
*Y = 0 corresponds to the tip of notch

Once, the specimen passes the peak load stage, the crack continues to open and propagate (Fig. 9). The brittleness of the specimen can be observed from this phenomenon. It is noted that in small size specimen (D1), the crack propagates slowly i.e. the corresponding length of the crack at the same notch opening is small in D1 as compared to D2 et D3. Moreover, the crack propagates more abruptly in the

D3 at post peak stage, thus showing a more brittle behaviour. This has been observed that as the specimen size becomes larger, the crack is more unstable and propagates more abruptly. In large (D3) and medium beams (D2), at about 80% of the maximum force in post peak region, crack branching is observed starting at a certain distance from the notch tip (Fig. 10). In D2 beam this distance is larger than that in the D3 beam. However, crack branching is not observed in the small beam (D1).

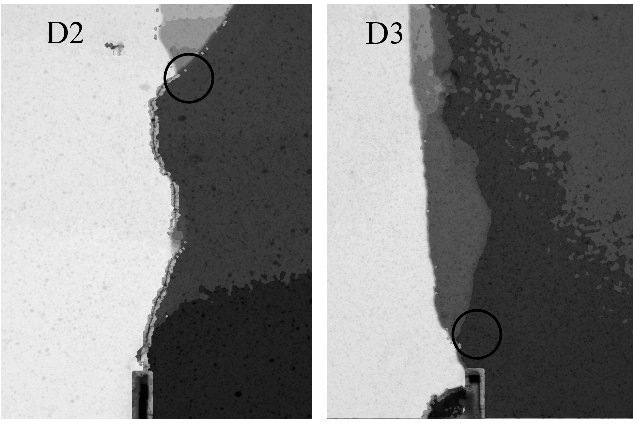


Figure 10. Crack branching at 80% F_{max} post peak stage.

5 CONCLUSIONS

An experimental study is performed in this paper to observe the cracking phenomenon in geometrically similar specimens. Digital image correlation technique is used in this study the cracking in concrete. This technique is proved very effective to measure crack opening displacement. Crack length can also be estimated based on the crack opening displacement data. A considerable size effect is noted on crack opening and crack propagation. It is observed that overall mechanical response of the structure (ductility, brittleness, size effect) can be understood well from the cracking mechanism in the structure. The current work will be completed in the next step with acoustic emission technique coupled with digital image correlation.

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